

# Utilization of eucalyptus for electricity production in Brazil via fast pyrolysis: A techno-economic analysis

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## ABSTRACT

A process model of a 2000 metric ton per day eucalyptus Tail Gas Reactive Pyrolysis (TGRP) and electricity generation plant was developed and simulated in Pro/II software for the purpose of evaluating its techno-economic viability in Brazil. Two scenarios were compared based on operational conditions in the country: a single biomass to bio-oil TGRP production facility and a distributed/satellite processing that consists of several small TGRP production facilities with aggregate capacity similar to the single one, both feeding into one centralized electricity generation plant. The selling price at the breakeven point of the electricity generated via TGRP was estimated to be US\$0.34 and US\$0.62 per kWh for the single and the distributed scenarios respectively, considering a 10-year payback period. The single capacity pyrolysis and electricity generation facility is found to have better economic benefits over the distributed plants of small sizes under the current conditions in Brazil. The results therefore indicate that pyrolysis of eucalyptus wood for electricity in a single facility cannot be competitive with the current electricity cost in Brazil (US\$0.08–0.13/kWh) at present time. Considering auxiliary benefits such as climate change and carbon credits, plus the continuous increasing in the electricity market price in Brazil, both scenarios could be competitive in the future.

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## 1. Introduction

The environmental degradation coupled with energy resource depletion in recent years has led to the emergence of alternative energy sources such as bio-oil derived from biomass. While fossil fuels are presently the prevalent and least expensive energy sources, energy derived from biomass, the largest renewable carbon resource, is considered sustainable in the long term. Electricity generation is regarded as one of the most promising possibilities for reaching commercial scale production [1] when considering biomass as a resource.

The installed capacity in Brazil based on renewable sources was 140 GW representing 76% of the total electricity generated in 2015. The main renewable source is the hydroelectric power plant that contributes 64% of the total electricity generated in Brazil; the biomass has a share of 8% [2]. However the hydroelectric power

generation in Brazil has proven to be vulnerable to extraneous scenarios leading to unpredictability since 2015, the year in which a severe drought affected the populated states of Sao Paulo and Rio de Janeiro, reducing the efficiency of hydroelectric power plants. As an alternative, thermoelectric plant operations increased to fill the gap, further expanding the use of fossil fuels thereby increasing greenhouse gas (GHG) emissions and the price of electricity [3]. According to the Brazilian Electricity Regulatory Agency (ANEEL), the industrial price of electricity in the Southeast region increased from 80.94 to 131.25 US\$/MWh during 2012–2016 [4].

Brazil is well known for its abundance of sugarcane bagasse. However, other potential biomass resources, such as eucalyptus, have proven to be a feasible resource for energy production via fast pyrolysis [5] and integrated gasification [6] due to its increased bulk density and higher calorific value compared to other woody biomass.

The pulp and paper industries have played an important role in the Brazilian economy and have encouraged farmers to grow eucalyptus on their arable lands. Although pulp and paper is an important market, there is a lot of volatility in the sector. The

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eucalyptus tree takes about 7 years to mature and during this period changes in the economy can negatively impact the supply chain, leaving growers with an unmarketable product. In the state of Goiás alone, many areas with 10-year old eucalyptus trees have found no potential buyers. In 2011, the total eucalyptus planted area was 4,873,952 ha with Minas Gerais and São Paulo as the leading producers [7].

Although biomass could be used directly for the production of electricity similar to coal combustion, it would be more expedient when the biomass handling and pretreatment processes are de-coupled from the actual electricity generation facility due to the low bulk density of the biomass. Considering the various thermochemical biomass conversion technologies, combustion and gasification included, fast pyrolysis is perhaps the best-suited technology to efficiently decouple biomass-to-electricity via the conversion of biomass into bio-oil and subsequently into electricity using turbines or compression ignition engines. Converting the biomass into intermediate liquids at several satellite sites before its use for electricity generation at a centralized location has the potential to increase efficiency and decrease capital costs [8].

Our group has expended much effort in investigating the behavior of bio-oil in thermal systems [9–11] and has moved beyond bench-scale bio-oil production with the development of the patented Combustion Reduction Integrated Pyrolysis System (CRIPS) [12] a 2 MTPD system demonstrated at up to 1 MTPD and having a DOE Technology Readiness Level of 6–7.

The location of the pyrolysis plant is an important decision in order to minimize the transportation costs of the feedstock. The electricity generation plant should be equally well located, since the electricity distribution point should be close to customers. Wright et al. [13] studied the logistics related to the distribution of the biomass and bio-oil processing unit in the United States of America. According to their concept, the ideal distribution is to have a central bio-oil processing unit surrounded by several pyrolysis plants, so that the high energy-dense material (bio-oil) is shipped instead of the low energy-dense material (wood), to reduce logistics costs.

Process modeling and simulation present essential tools for the critical technical and economic review of process performances. Techno-economic analyses (TEA) of electricity generation from fast pyrolysis oil using process models and simulation software have not been studied extensively in the literature. Nonetheless, several authors [14–16] have used TEA to evaluate the minimum selling price (MSP) of pyrolysis oil and upgraded bio-oil based on different biomass capacities ranging from 10 to 2000 MTPD (metric ton per day). Based on different assumptions made by these authors, the MSP of bio-oil has been estimated to be between US\$0.20/kg to US\$0.50/kg.

The objective of this paper is to evaluate the economic viability of electricity production from fast pyrolysis oil with eucalyptus as the main feedstock. A 2000 MTPD (distributed) and a single 2000 MTPD pyrolysis and power generation facilities are modeled and the total capital investment and unit production cost of electricity are estimated. The effect of critical factors on the cost of electricity production for the proposed plant is also evaluated through sensitivity analyses.

## 2. Material and methods

### 2.1. Process description, modeling and simulation

The generation of electricity from pyrolysis oil proposed in this study consists of four sectors (Fig. 1): (1) biomass cultivation, U1; (2) biomass pretreatment, U2; (3) biomass fast pyrolysis, U3 and (4) electricity generation, U4; from pyrolysis oil. U3 was developed and

simulated in the SimSci PRO/II<sup>®</sup> software. With the technical parameters from the basic design of the plant and input assumptions specified, the software was used to generate the mass and energy balances that were further used as basis for the techno-economic analysis.

#### 2.1.1. Feedstock cultivation, transportation and pretreatment

About 10–40% of total production cost is usually incurred during biomass cultivation, harvesting, shredding, compacting, collection [17] and for that reason these factors must be evaluated for their economic impact. The pre-treatment of woody biomass is a set of unit operations that are mandatory in order to enable the feedstock amenable to pyrolysis conversion: reception, grinding, screening, drying and storage. Feedstock logistics are necessary to guarantee a continuous supply to the industry [18]. Eucalyptus trees were mechanically harvested (cut and debarked) and allowed to dry on the field for 180 days until their moisture content was around 30% before use. The debarked trunks were road transported to the biomass pre-treatment area (i.e. U1, Fig. 1). In this area, wood trunks were chopped into smaller pieces, dried to about 10 wt% moisture content, and milled to 2 mm particle size. The pre-treated biomass was transported to section 2 (i.e. U2, Fig. 1), to be converted via fast pyrolysis. A 2–3 mm particle size range is consistent with fluidized-bed pyrolysis where high specific surface area of the feedstock is necessary to achieve the heat rate associated with fast pyrolysis. While sawdust fits this particle size range and could reduce the production costs if used, our goal in this paper was to present the processing of eucalyptus by producers within the bio-refinery concept. For that reason, our starting feedstock comprises eucalyptus trees and not sawdust.

However these feedstock pretreatment unit operations were not sized by in PRO/II modeling, rather, the capital and operating costs of vendor suggested units were considered. Power requirements for biomass grinding were calculated based on average specific energy consumption presented by Mani et al. [19]. For drying operations, it was assumed that 5 MJ per kg of water is evaporated [14].

#### 2.1.2. Tail gas reactive pyrolysis (TGRP)

TGRP is a fluidized-bed pyrolysis process developed at the Agricultural Research Service (ARS) laboratory of U.S. Department of Agriculture (USDA), Wyndmoor, PA. The patented process uses a reactive atmosphere created by a fluidizing medium recycled from the tail gas of the fluidized-bed reactor instead of an inert gas medium [20]. An on-farm/in-forest autogenic pyrolysis system is selected based on the patented Combustion Reduction Integrated Pyrolysis System (CRIPS) [12] developed by the USDA and the University of Pretoria (South Africa) that uses part of the system's own energy generated in an external combustor to provide for the endothermic pyrolysis reactions of the TGRP. The system comprises two reactors: a pyrolysis reactor fluidized with the tail gas (reduction bed) integrated with a combustion reactor fluidized with air (oxidizing bed). After the pyrolysis reaction the spent sand and residual char is introduced into the combustion bed where the sand is reheated by combustion of the residual char and returned to the pyrolysis reactor. A detailed explanation about the integrated CRIPS-TGRP process description and its modeling using PRO/II software is presented in the Electronic Supplementary Material. In this paper, bio-oil refers to the fraction collected in the electrostatic separator (ESP).

#### 2.1.3. Electricity production

The bio-oil (S15, Fig. S1) is transported from the pyrolysis section to the power generation unit where it fuels a steam boiler that drives a steam turbine for electricity generation. For ease of

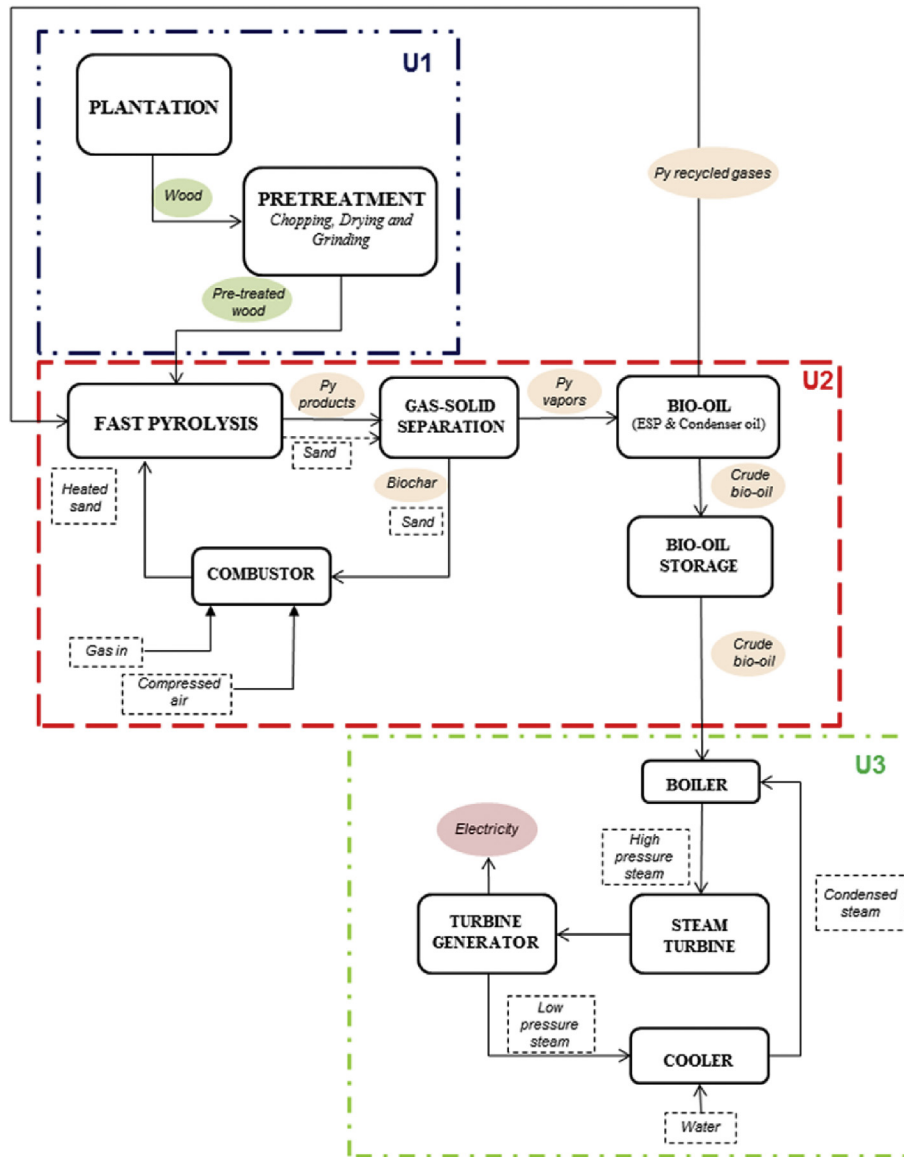


Fig. 1. Process flow diagram of electricity generation from fast pyrolysis oil.

calculation, the following assumptions were made: the boiler is an adiabatic combustor with an efficiency of 80%, the superheated steam is at 500 °C and 8600 kPa with an isentropic efficiency of the multi-stage turbine at 80%, the electricity generation efficiency is 85% and parasitic loads are 10%. With this the amount of electricity generated in the plant for the input biomass based on TGRP bio-oil yield is estimated at 110 MW.

## 2.2. Process economics

The estimation of total capital investment (TCI) includes all the costs involved in the plant design, building and commissioning. Based on the TCI, the total production cost (TPC) for the whole plant, which also consists of the costs for producing electricity from eucalyptus fast pyrolysis oil, is also estimated. Table 1 shows the assumptions based on which the economic evaluation was estimated.

Table 1

Criteria, assumptions and prices for economic calculations.

| Parameter                            | Unit                | Value  |
|--------------------------------------|---------------------|--------|
| Plant Location                       | —                   | Brazil |
| Cost year for analysis               | —                   | 2016   |
| Plant capacity                       | ton/day             | 2000   |
| Financing                            | % owned capital     | 100    |
| Plant availability (90%)             | days/year           | 329    |
| Plant construction period (PCP) [14] | months              | 24     |
| Startup time (25% PCP) [14]          | months              | 6      |
| Plant depreciation period            | years               | 10     |
| Project economic life                | years               | 20     |
| Corporation tax rate                 | %                   | 35     |
| Return on investment                 | %                   | 10     |
| Electricity cost [4]                 | US\$/kWh            | 0.13   |
| Water Cost [27]                      | US\$/m <sup>3</sup> | 0.02   |
| Feedstock production cost [28]       | US\$/ton            | 50.00  |
| Feedstock Transportation cost        | US\$/ton/km         | 0.42   |

The factorial method used by various authors [14,21,22] was applied to estimate the TCI for the entire plant based on the total cost of purchased equipment (TPEC); other costs were calculated as factors of the equipment cost. The TCI and TPC are subsequently employed for the analysis of discounted cash flow rate of return (DCFRROR). The depreciation method used was the Modified Accelerated Cost Recovery System (MACRS) [14].

TPEC was evaluated based on the equipment costs and quotations received from vendors in Brazil. Unit costs of equipment are scaled from base equipment cost following Equation (1) [21]. All the costs were obtained in Brazilian local currency (R\$ - Real) and converted to US Dollar using a money exchange of US\$1.00 equivalent to R\$3.20 (March 2017). The shipping costs for the biomass and bio-oil were obtained from a website specialized in freight costs [23].

$$Cost_{EqNew} = Cost_{EqBase} * \left( \frac{Cap_{New}}{Cap_{Base}} \right)^n \quad (1)$$

where,  $Cost_{EqNew}$  is the scaled new equipment cost (US\$),  $Cost_{EqBase}$  is the cost of the base equipment,  $n$  is the specific scaling factor for a particular equipment (ranging from 0.6 to 0.8) [24],  $Cap_{New}$  and  $Cap_{Base}$  are the sizes of the new and base equipment respectively.

TPC generally depends on the type of technology employed, plant capacity and biomass feedstock type, and it is estimated from the variable operating cost (VOC), fixed operating cost (FOC) and general expenses (GE) which are all calculated as factors of the Fixed Capital Investment (FCI). The VOC comprises the costs of utilities, raw materials and transportation. The FOC consists of the costs involved with maintenance, operating labor, supervision, administration, plant overheads, insurance and local taxes. Operating labor is the cost for hiring and paying workers with the assumption of an 8 h and 5 shifts system. The number of workers and their positions were defined based on work of Phillips et al. [25]. The salary is presented on Table S1. The unit production cost of electricity can therefore be calculated by dividing the annual TPC by the annual electricity output.

Minimum electricity and bio-oil selling prices (MSP) were estimated under a 10% IRR based on the DCFRROR analysis taking into account operating and capital costs [26]. The MSP was calculated for a 10 years payback period.

### 2.3. Distributed biomass processing and centralized bio-oil facilities

For the distributed biomass processing plant it was assumed that 10 biomass processing facilities, each of 200 MTPD capacity, are distributed over a set radius that supply TGRP bio-oil to a centralized power generation plant to generate electricity using the bio-oil as boiler fuel (total bio-oil amount of 580 MTPD). To estimate the average biomass transportation distance ( $r_B$ ) to place the centralized power station we use Equation (2) [13]. This assumes that the power plant is stationed at the center of a square grid along which the satellite biomass-bio-oil conversion mini plants are located. For a rectangular grid road layout, tortuosity factor of  $\tau = 1.5$  is considered where  $\tau = 1$  corresponds to a straight line trajectory between two given points. Having established  $r_B$  the average bio-oil transportation distance ( $r_{BO}$ ) becomes a function of amount of biomass that must be converted to bio-oil and the size of the distributed pyrolysis plants, expressed by Equation (3).

$$r_B = \frac{1}{6} \tau \sqrt{\frac{F}{Yf}} (\sqrt{2} + \ln(1 + \sqrt{2})) \quad (2)$$

$$r_{BO} = 0.423 \tau \left( \frac{F}{F_{plant}} \right)^{0.476} \sqrt{\frac{F_{plant}}{Yf}} \quad (3)$$

where  $\tau$  is the tortuosity factor,  $F$  is the biomass input (ton/year),  $Y$  is the biomass yield (ton/ha), the factor  $f$  is the fraction of land surrounding the plant that is devoted to biomass crops (%).  $F_{plant}$  is the bio-oil input (ton/year).

## 3. Results and discussion

### 3.1. Tail gas reactive fast pyrolysis (TGRP) process modeling

The simulated process model for the 2000 MTPD resulted in TGRP bio-oil and biochar in the amounts of 580 MTPD (water content of 2.5 wt%) and 224 MTPD respectively. About 55 vol% of NCG generated was recycled into the pyrolysis reactor for process heat generation. TGRP process produces bio-oil comparable in quality to the catalytic fast pyrolysis (CFP) oil [29] but without the use of catalyst and thereby the associated purchase cost or capital engineering cost. Both are often associated with lower liquid yield than conventional pyrolysis carried out in an inert atmosphere on a mass basis [5] because of its ability to reject oxygen in the liquid product as water, CO or CO<sub>2</sub>. This is yield reduction that is welcome as a high quality bio-oil will have a better performance in terms of combustion in a boiler.

The stream values for the integrated CRIPS-TGRP process are presented in Table S2; Table S3 summarizes the mass balance of the pyrolysis reaction for the 2000 MTPD facility and Table S4 presents the characterization of the feedstock, pyrolysis oil and biochar obtained from fast pyrolysis of eucalyptus (Electronic Supplementary Material). The pyrolysis oil obtained had a higher heating value (HHV) of 30.76 MJ/kg (dry basis, db) which is higher than that for pyrolysis oil obtained from wood via traditional fast pyrolysis. In terms of energy content, the TGRP bio-oil produces 8648.72 MJ/ton of biomass while the traditional fast pyrolysis oil is 7374.76 MJ/ton.

### 3.2. Economic performance

The TPEC for the various production units are presented in Table 2. The fast pyrolysis unit contributed to 85% (or US\$ 38.7 million) of the 2000 MTPD facility's TPEC followed by the electricity generation section (15% of the plant's TPEC). These costs resulted in plant TIC of approximately US\$ 137.9 million for the 2000 MTPD facility and this cost was mainly driven by the use of pyrolysis and combustion reactors, boiler, turbines, generators, dryers etc. For the distributed arrangement, the fast pyrolysis equipment accounts for 93.3% of the TPEC while the electricity generation accounts for 6.7% of the TPEC. The TIC for the distributed case is US\$ 314.4 million. Li et al. [16] obtained a TCI of US\$ 273 million for a 2000 MTPD fast

**Table 2**  
Installed equipment costs.

| Unit                                  | 2000 MTPD<br>(M\$) | 10 × 200 MTPD<br>(M\$) |
|---------------------------------------|--------------------|------------------------|
| Feedstock handling and Pretreatment   | 5.60               | 14.07                  |
| Pyrolysis                             | 12.70              | 31.89                  |
| Quench                                | 7.43               | 18.67                  |
| Heat recovery                         | 12.26              | 30.79                  |
| Product recovery and storage          | 0.66               | 1.66                   |
| Electricity production                | 7.01               | 7.01                   |
| Total Purchased Equipment Cost (TPEC) | 45.66              | 104.09                 |
| Total Installed Cost (TIC)            | 137.89             | 314.36                 |

pyrolysis and gasification facility for electricity production and Carrasco et al. [30] obtained US\$ 87.4 million for a 2000 MTPD (biomass pretreatment and pyrolysis plant). The TPC for the single 2000 MTPD facility was estimated at approximately US\$ 57.4 million with the VOC (comprising the costs of feedstock and utilities) accounting for the highest share of 80.6%. These results are analogous to other TEA studies which reported high percentage of the TPC being attributed to feedstock and utilities costs [31,32]. The TPC for the distributed facility was US\$ 74.2 million and the VOC has the highest share (66.5%).

Fig. 2 shows the variation in annual VOC, FOC and general expenses with respect to plant capacity. Except for the feedstock and utilities costs that were calculated, other costs were estimated using a Lang factor of 0.6 resulting in electricity production costs as depicted in Fig. 2.

Although in this study the bio-oil is not sold as a commodity fuel, the unit production cost was still calculated since this cost is of interest to many Brazilian researchers and investors. The unit production cost of the TGRP bio-oil was calculated at US\$0.25 and US\$0.31 per liter (US\$0.29 and US\$0.37 per kilogram) for the single 2000 MTPD and for the distributed plants, respectively.

Of the total electricity generated in the plant, 40% was exported to the grid. Based on this, the electricity production cost of US\$0.17 per kWh was estimated for the single 2000 MTPD plant and US\$0.23 per kWh for the distributed case.

Regardless of the fact that comparative analysis has not been carried out with regard to similar quality bio-oil produced from CFP, it is worth mentioning that the catalysts costs can be around US\$0.94 per liter of bio-oil obtained using CFP according to Li et al. [33]. This is avoided costs that the TGRP process beneficiaries.

Bio-oil production cost varies significantly depending upon the technology applied, feedstock type and scale of production, as presented in Table 3. In the paper published by Bridgwater et al.

**Table 4**

Summary of economic analysis.

| Economic Indicator                  | 2000 MTPD | 10 × 200 MTPD |
|-------------------------------------|-----------|---------------|
| Fixed Capital Investment (FCI, M\$) | 214.2     | 488.4         |
| Working Capital (WC, M\$)           | 32.1      | 73.3          |
| Total Capital Investment (TCI, M\$) | 249.1     | 567.9         |
| Project Contingency (M\$)           | 35.7      | 81.4          |
| Minimum Selling Price (\$/kWh)      | 0.34      | 0.62          |

[34], a production cost of US\$0.08/kWh electricity was reported considering a \$2400/kW facility.

A summary of economic analysis is presented in Table 4.

### 3.3. Minimum selling price (MSP)

The MSP for electricity and bio-oil were calculated at the breakeven point where total revenues and total costs are equal [35]. The MSP was calculated as US\$0.34/kWh and US\$0.62/kWh, for the single 2000 MTPD and distributed pyrolysis facilities respectively. The cash flow for both scenarios is presented in Figs. S2 and S3 (Electronic Supplementary Material). The range for the last 5 year-Sao Paulo State kilowatt hour selling prices for the industry sector was US\$0.08/kWh to US\$0.13/kWh.

The Brazilian sugarcane industry uses residual bagasse to generate steam and electricity in a boiler-steam turbine system. Carpio & Souza [36] estimated the cost of bioelectricity production in a plant capable of processing 130 Mton of bagasse having a 50% moisture content and a heating value of 7.5 MJ/kg. Based on their results, each ton of bagasse yields an average of 3 MWh with 70% available to export. The authors estimated the cost of bioelectricity production as 60 US\$/MWh in a scenario where 91% of the bagasse is used for electricity generation and the balance for second generation ethanol production.

However this may not be a fair comparison since the sugarcane bagasse is already available and collected at the sugar processing plant site. No additional transportation cost is incurred when the electricity generation plant is co-located at the plant site and, for that reason, the electricity would be less expensive than that obtained from wood pyrolysis.

In terms of electricity production efficiency, a boiler-steam turbine system based on sugarcane bagasse is much more efficient when compared to the wood pyrolysis. In our study, 1.32 MWh/ton of wood can be obtained and due to the high consumption of energy necessary to grind and dry wood, the amount of energy available to export is only 40%.

As a way of salvaging Brazil's current severe drought problem and high electricity prices, the thermochemical conversion of Brazilian agricultural residues and other available biomass into electricity through the pyrolysis platform would do more good than harm. It is important to highlight that many places in the world are trying to reduce GHG (greenhouse gas) emissions caused by fossil fuels, thus clean technologies to produce electricity are highly sought after. Life cycle analysis (LCA) would be required to estimate the climate change benefits and weighed with the economics. Pourhashem et al. [37] performed a LCA for a 200 MTPD corn stover facility for which the bio-oil and biochar produced were used to generate electricity and/or used as a soil amendment, respectively. Their results indicated that combusting bio-oil to generate electricity had a lower GHG emission (84 g CO<sub>2</sub>/kWh) when compared to the fossil fuels (1200 g CO<sub>2</sub>/kWh). Besides the large reduction in GHG another important aspect of using bio-oil for electricity generation is that carbon credits can be generated. The revenue generated from carbon credits can contribute to a reduced electricity production cost.

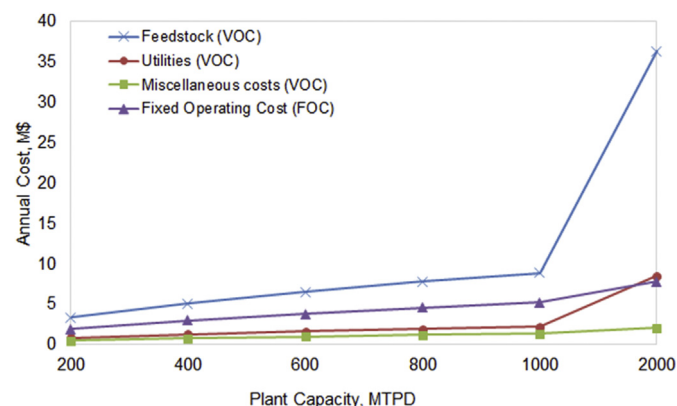


**Fig. 2.** Total production cost of electricity production for different plant capacities.

**Table 3**

Selling price of bio-oil from different studies.

| Country | Biomass   | Biomass capacity (MTPD) | Bio-oil yield (10 <sup>3</sup> L/h) | Bio-oil cost (US\$/L) <sup>a</sup> | Ref.       |
|---------|-----------|-------------------------|-------------------------------------|------------------------------------|------------|
| US      | "biomass" | 1650                    | 24                                  | 0.95                               | 35         |
| Brazil  | Wood      | 2000                    | 20                                  | 0.58                               | This study |
| US      | Wood      | 550                     | 13                                  | 0.30                               | 36         |
| Finland | Wood      | 184                     | 6                                   | 0.24                               | 37         |
| US      | Wood      | 400                     | 6                                   | 0.24                               | 38         |
| UK      | Wood      | 1000                    | 28                                  | 0.15                               | 39         |

<sup>a</sup> Conversion based on bio-oil density of 1.20 kg/L and high heating value of 30.76 MJ/kg (this study). The cost reported for this study is the Minimum Selling Price (MSP).

If a company's interest lies in the bio-oil instead of using it to produce electricity, then the minimum selling price would be US\$0.58/L (US\$0.02/MJ) and US\$1.04/L (US\$0.03/MJ), for the single 2000 MTPD and distributed pyrolysis facilities respectively. In Brazil, some companies are selling the boiler fuel oil at an average of US\$0.01/MJ.

### 3.4. Sensitivity analysis

Sensitivity analysis was carried out to identify parameters that have significant impacts on the MSP over the range that the parameters are expected to vary. In this study, the variation range was set to  $\pm 30\%$  of the base case for all the parameters evaluated including tax rate, biomass cost, IRR, fixed capital investment, and electricity production. The results were plotted in tornado diagrams for 2000 TPD and distributed electricity production as shown in Fig. 3a and b respectively.

For the single 2000 MTPD facility, the MSP for the electricity is affected mainly by the amount of electricity that is produced and the fixed capital investment. In order to evaluate the impact of the amount of electricity produced in the electricity cost, it was assumed that it is possible to increase the bio-oil yield based on the

improvement on the pyrolysis facility. One way to increase the bio-oil yield is improving the separation of water from the bio-oil, allowing greater utilization of the condenser oil with a lower water content so that it can also be used to fuel the boiler together with the electrostatic separator fraction (ESP).

It was possible to reduce the selling price of electricity to US\$0.26/kWh by increasing the amount of energy generated by 30%. The MSP obtained in a distributed facility was mainly affected by the electricity production. The lowest price (US\$0.47/kWh) was obtained when the electricity production was increased by 30%. The biomass cost had the lowest effect on the electricity-selling price, reducing the price to US\$0.58/kWh.

### 3.5. Calculated distances and the distributed biomass case

The maximum distances that the eucalyptus trees must be transported to feed the facilities and the distance to ship the bio-oil were calculated using Equations (2) and (3). The logistics regarding the eucalyptus trees differ from other agricultural crops since the trees can be harvested three times during their lifetime and cutting can be performed every 7 years.

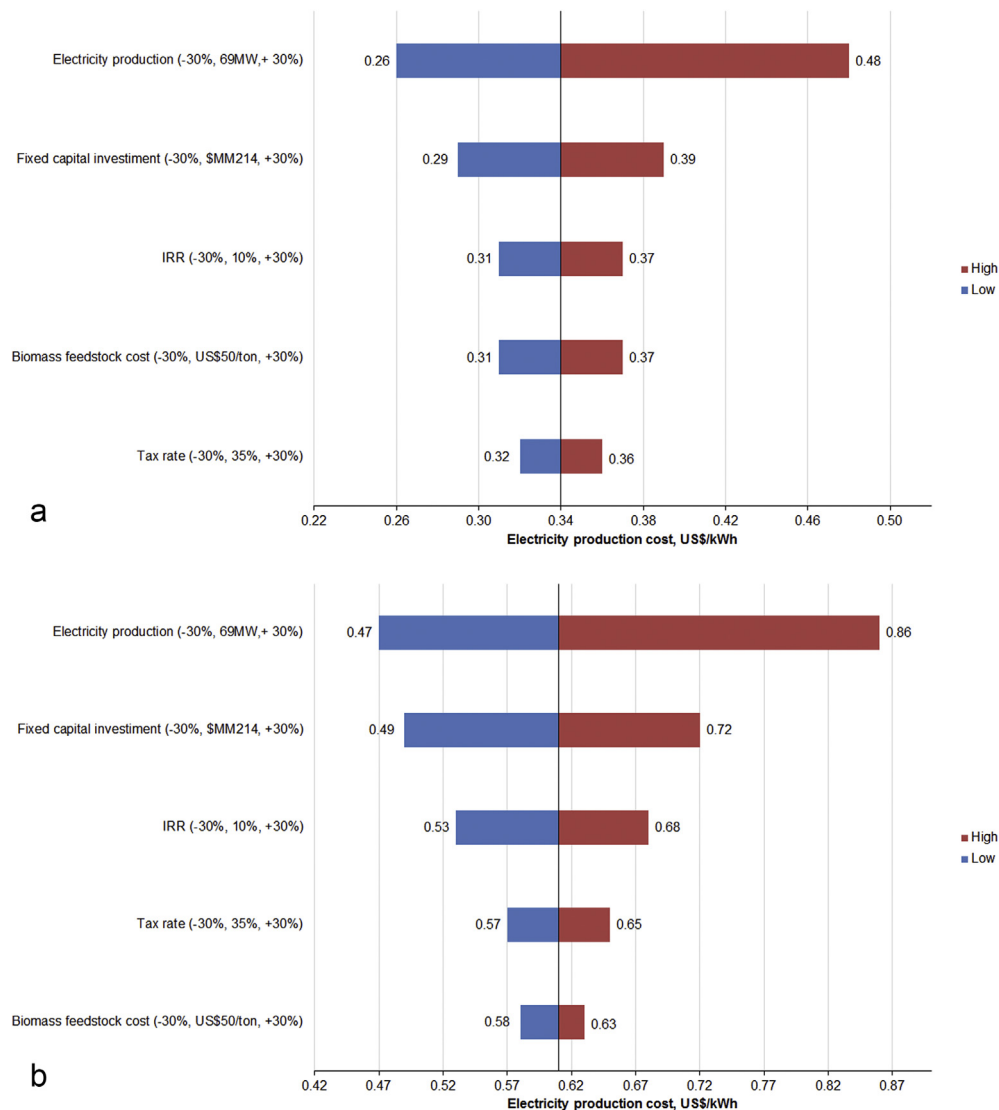


Fig. 3. a: Sensitivity analysis results for the 2000 MTPD plant. b: Sensitivity analysis results for the distributed plant.

The distributed 2000 MTPD plant has a high investment cost leading to a high electricity unit production cost when compared to the single 2000 MTPD facility. In other words, assuming the same capacity (2000 MTPD), it is more expensive to buy 10 small plants than to buy a single high capacity plant. One advantage of the distributed arrangement is its flexibility regarding the feedstock mobility. For example, it is possible to have 4 units operating with eucalyptus and 6 units operating with other crops e.g., grass. Another advantage pertains to maintenance and operation that can be easier and less expensive for distributed processing than for the single 2000 MTPD unit.

When considering the single 2000 MTPD pyrolysis plant, the eucalyptus shipment distance was estimated at 4.6 km in the first year with the radius constantly increasing over the 7 years of cultivation up to 12.4 km. After 7 years, the first area can be harvested again and the cycle repeats. The associated shipping distance for the bio-oil produced to the electricity generation facility is 13.7 km. Since in the distributed case, it was considered that 10 units could process 200 MTPD of wood, the distance to ship the feedstock is 1.5 km in the first year and the radius is constantly increased along the 7 years up to 3.9 km. The bio-oil processing facility in this case is capable to process the same amount of the bio-oil produced in the 2000 MTPD hence the distance calculated using Eq. (3) is about the same (i.e. 13.4 km).

#### 4. Conclusion

The quality of the bio-oil obtained from the TGRP process based on its product distribution is not only suitable for electricity generation but can be used as commodity fuels, chemicals and other value-added bio-products. The MSPs for bio-oil were calculated as US\$1.04/L and US\$0.58/L, for the distributed and single 2000 MTPD, respectively. The MSPs for the electricity were estimated at US\$0.62 and US\$0.34 per kWh for the distributed and 2000 MTPD respectively.

The industrial price of electricity in the Southeast region of Brazil ranged from 0.08 to 0.13 US\$/kWh from the year of 2012–2016 according to the Brazilian Electricity Regulatory Agency (ANEEL). Considering the results presented in this paper, the utilization of bio-oil to generate electricity in a single pyrolysis facility cannot be economically competitive with the electricity based on hydroelectric power or thermoelectric plants in Brazil in the current market. Due to the constant increase in the electricity prices, cyclic crises in the Brazilian wood sector, and GHG emissions concerns, the pyrolysis of eucalyptus wood to electricity might be economically competitive in the near term. The installation of a facility such as the one proposed in this study in areas where there is no electricity, for example in the middle of the Amazon rainforest or in some border region, can help to justify the investment. Also, it is well known that both the sugarcane and the pulp and paper industries demand power (electric and thermal) and fuel. Furthermore, in a troubled economic environment, it is necessary to find alternatives to enhance business opportunities for these sectors, so it is prudent to envision a pyrolysis plant co-located with the sugarcane and the pulp and paper industries in a biorefinery concept.

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#### Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://doi.org/10.1016/j.renene.2017.12.036>.

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